The Determination of Cloud Optical Thickness and Effective Particle Size From Measurements of Transmitted Solar Diffuse Light

A. A. Kokhanovsky, P. J. McBride, K. S. Schmidt, and P. Pilewskie

***Abstract*—A new dual-channel method for determining cloud optical thickness and cloud particle size is presented. The method is applied to both the experimental measurements of cloud transmittance and also to a synthetic data set derived from the numerical solution of the radiative transfer equation. The results of the validation show that the technique can be, indeed, applied to optically thick clouds. The technique is superior with respect to its speed and flexibility and with respect to existing up-to-date cloud retrieval methods based on the measurements of the transmitted solar light.**

***Index Terms*—Clouds, radiative transfer, remote sensing.**

I. Introduction

BECAUSE clouds are strong modulators of the transport of shortwave and infrared radiative energy, they are significant drivers of weather and climate. Therefore, various techniques have been developed to monitor cloud radiative and microphysical properties using ground, airborne, and satellite instrumentation [7], [17]. References [3] and [16] have used the terrestrial window information within the 750–1250-cm^{-1} spectral band to infer the ice cloud optical thickness (COT) and effective particle size. In the shortwave spectral range, COT τ and effective cloud particle radius (ER) a_{ef} are usually retrieved using a dual-channel solar reflectance method (e.g., [12]). A similar method applied to measurements of transmitted solar radiation was developed in [4]. Reference [2] has developed a technique for the determination of COT using the spectroradiometer nadir transmittance measurements at a wavelength of 1 μm assuming the effective radius of particles. The independent measurements of the cloud liquid water path (LWP) using microwave radiometer and derived COT were used to determine ER. In addition, [2] has developed a method for the determination of COT and ER using the downward shortwave surface irradiance measurements in combination with the LWP microwave measurements. Reference [9] has used the two-stream approximation to retrieve the COT from the diffuse transmittance measurements.

It was found in [10] that the dual-channel solar light transmittance method produces the best results in a range of COT between 25 and 40. For COTs outside of this range, a dual-channel method (DCM) applied to the transmitted solar light generally leads to larger uncertainties. To overcome this problem, [10] developed a spectral method for determining both COT and ER, based on the analysis of the slope of the cloud transmission function in the spectral range 1565–1634 nm and the transmission at 515 nm. The use of the slope in the near infrared improves the accuracy and uniqueness of the retrieval compared to the standard DCM [10].

This paper presents a variation of the dual-channel and spectral methods based on the analytical solution of the radiative transfer equation valid at large values of COT. Because the method is simple, it can be used for *real-time* analysis in the field, when computational speed is critical. This new method also helps in understanding the physics behind the standard look-up table (LUT) based approach. The method can be applied to appropriate combinations of wavelengths without the need for extensive forward modeling that is required to create the large LUTs.

The structure of this paper is as follows. In Section II, we present the main equations for the cloud transmission function in the visible and near infrared. In Section III, the semianalytical solution of the corresponding inverse problem is presented, along with the analysis of the accuracy of retrievals.

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II. Transmission Function of a Cloud Over a Reflective Surface

We will use the exponential approximation of the asymptotic radiative transfer theory valid for COT larger than approximately 10 and for weak absorption (single scattering albedo close to unity). This theory is described in [7] and [18]. The final equation for the cloud transmission function can be written as

$$T(\tau,\xi,\eta) = t(\tau)K(\xi)K(\eta) + \frac{At(\tau)K(\xi)\Re(\eta)}{1-Ar} \quad (1)$$

where the second term on the right accounts for the Lambertian ground reflectance with albedo A. The variables in (1) can be

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TABLE I
COEFFICIENTS OF THE PARAMETERIZATION FOR THE FUNCTION $p(x_{\mathrm{ef}})$ [SEE (3)]

parameter/wavelength	1.548 μm	1.634 μm
p_0	1.34965	0.98369
p_1	0.5834	0.98278
ε	0.12162	0.11075
σ	0.16037	0.18856

derived from the following analytical equations [7]:

$$
\begin{aligned}
t(\tau) &= \frac{\sinh y}{\sinh(\alpha y + x)}\\
K(\xi) &= \frac{3}{7}(1+2\xi)\\
\Re(\eta) &= \exp\left(-yK_0(\eta)\right) - t(\tau)\exp(-x-y)K_0(\eta)\\
r &= \exp(-y) - t(\tau)\exp(-x-y)\\
\alpha &= 1.072 \quad x=\gamma\tau \quad y=\gamma c\\
\gamma &= \sqrt{3b\beta} \quad c = 4/3b.
\end{aligned}
\tag{2}
$$

Here, t is the cloud diffuse transmittance coefficient for the diffuse light illumination conditions; ξ is the cosine of the solar zenith angle; η is the cosine of the viewing zenith angle; $b = 1-g$, where g is the asymmetry parameter; and β is the probability of photon absorption, co-albedo, or 1-single scattering albedo or, equivalently, the ratio of the absorption coefficient κ_{abs} to the extinction coefficient κ_{ext}. The analytical relationship between the cloud transmission function and the cloud microstructure parameters can be obtained if one uses the parameterizations for b, β, and κ_{ext}, all of which are functions of ER. In particular, the following parameterizations can be derived using Mie calculations (e.g., see [5]):

$$
\begin{aligned}
b &= \varphi_0 + \varphi_1 x_{\mathrm{ef}}^{-2/3} + \varphi_2 x_{\mathrm{ef}}^{-4/3}\\
\beta &= p(x_{\mathrm{ef}})\chi x_{\mathrm{ef}}\\
\tau &= \kappa_{\mathrm{ext}}\ell = \frac{1.5ws}{\rho a_{\mathrm{ef}}}
\end{aligned}
\tag{3}
$$

where $x_{\mathrm{ef}} = ka_{\mathrm{ef}}$, $k = 2\pi/\lambda$, χ is the imaginary part of the refractive index of water at wavelength λ, ρ is the density of water, w is the LWP, $p(x_{\mathrm{ef}}) = p_0 + p_1\exp(-2(x_{\mathrm{ef}}^{-2/3}-\varepsilon)^2/\sigma^2)$, and $s = (1+1.1x_{\mathrm{ef}}^{-2/3})$. The constants p_0, p_1, ε, and σ are given in Table I (the value of p is close to 1.8 at 1548 nm and 1.85 at 1634 nm). We found that $\varphi_0 = 0.1$, $\varphi_1 = 0.5$, and $\varphi_2 = 1.4$ in the near infrared where water is weakly absorbing. At 865 nm, we derived $\beta = 0$, $\varphi_0 = 0.1115$, $\varphi_1 = 0.4513$, and $\varphi_2 = 1.2719$. We have assumed that the cloud is a vertically homogeneous turbid medium with a geometrical thickness ℓ, and therefore, $\tau = \kappa_{\mathrm{ext}}\ell$.

The relative biases of (3) compared to the exact solutions to the Mie theory are less than 2% in the visible and in the wavelength range 1548–1634 nm used in [10]. Note that (3) is also valid for ice clouds as well, with b equal to 0.25, p equal to 2.5 [6], [7], ρ as the *density of ice*, and w as the *ice water path*. The generalization for the case of mixed-phase clouds is straightforward. It should be pointed out that the retrievals for ice and mixed-phase clouds are shape dependent.

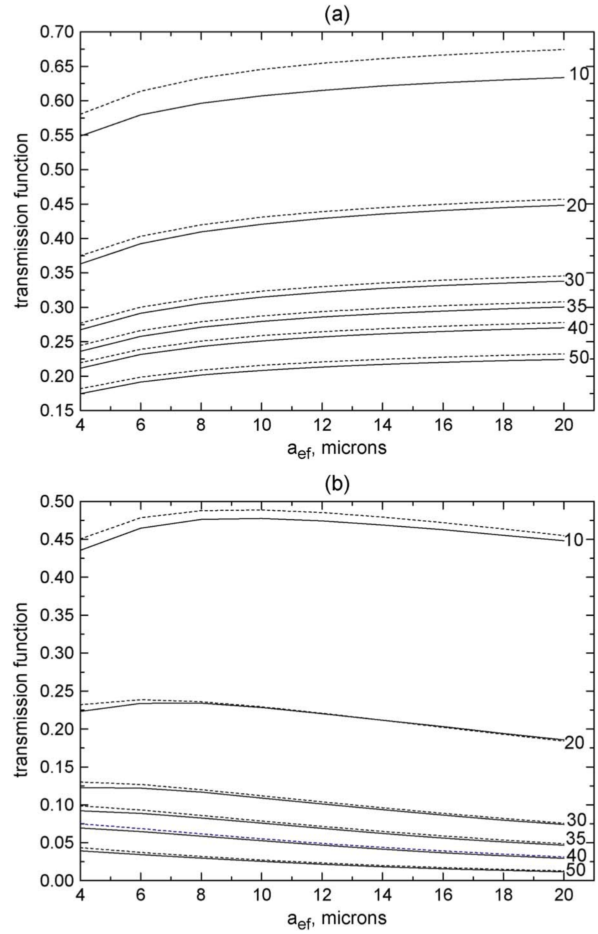

Fig. 1. Transmission function in the zenith viewing direction, calculated using the exponential approximation (dotted curves) and exact radiative transfer calculations (solid curves) as function of the effective radius, with a surface albedo of zero, $\xi = 0.75$, and COT = 10, 20, 30, 35, 40, and 50. (a) $\lambda = 0.865$ μm. (b) $\lambda = 1.548$ μm.

Different results for COT and ER are obtained by assuming different crystal habits in the retrieval process. The solutions to (1)–(3) compared to the exact radiative transfer calculations in the framework of the discrete ordinate method [15] are presented in Fig. 1 for the case of optically thick water clouds. The gamma particle size distribution (PSD) was assumed in the calculations: $f(a) = Aa^6\exp(-9a/a_{\mathrm{ef}})$, where A is the normalization constant and a is the radius of particles.

It is evident from Fig. 1(a) that the transmission function is a weak function of the effective radius at 865 nm, which means that precise information on the effective radius (or its spatial distribution in a cloud) is not needed for accurate retrievals of COT [2]. The cloud transmissivity increases slightly with ER in the visible, because forward scattering and, therefore, asymmetry parameter increase with ER. The behavior of the transmissivity in the near infrared is different. For large values of COT [e.g., larger than 30; see Fig. 1(b)], it decreases with increasing effective radius, dominated by droplet absorption that scales linearly with droplet size for weakly absorbing particles much larger than the wavelength of incident radiation. For smaller values of COT [e.g., COT = 10; see Fig. 1(b)], the cloud transmissivity first increases with ER, where forward scattering dominates, and then asymptotically decreases due to

the prevailing impact of particle absorption. Similar findings have been reported in [4], [10], and [14]. Based on the results shown in Fig. 1, we conclude that the accuracy of the analytical equations presented here is sufficient for determining COT and ER at values of COT larger than approximately 10.

III. Inversion Problem

Due to the simplicity of the equations involved, the development of a semianalytical retrieval procedure is possible. First, we apply these equations to the DCM. It follows from (1) that

$$T_1(\tau_1,\xi,\eta) = t_1(\tau_1)K(\xi)K(\eta) + \frac{A_1 t_1(\tau_1)K(\xi)\left(1 - t_1(\tau_1)K(\eta)\right)}{1 - A_1\left(1 - t_1(\tau_1)\right)} \tag{4}$$

$$T_2(\tau_2,\xi,\eta) = t_2(\tau_2)K(\xi)K(\eta) + \frac{A_2 t_2(\tau_2)K(\xi)\Re_2(\eta)}{1 - A_2 r_2(\tau_2)} \tag{5}$$

where indices 1 and 2 signify the wavelengths used [1—the channel where water clouds can be considered as nonabsorbing light scattering media (e.g., in the visible) and 2—the channel where the cloud transmittance depends on the droplet size distribution (in the near IR)]. Equation (4) follows from (1) for conservative scattering (no absorption, so $\beta = 0$). One can determine the diffuse transmittance coefficient t_1 (under conditions of diffuse illumination) from (1). Namely, it follows that

$$t_1(\tau_1) = \frac{T_1 - A_1 K(\xi)}{(1 - A_1)K(\xi)K(\eta) + A_1(1 - T_1)}. \tag{6}$$

On the other hand, it follows from (2) for $\beta = 0$ that

$$t_1(\tau_1) = \frac{1}{\alpha + 0.75\tau_1(1 - g_1)}. \tag{7}$$

Therefore, one derives

$$\tau_1 = \frac{4(t_1^{-1} - \alpha)}{3(1 - g_1)}. \tag{8}$$

Therefore, we have obtained an expression [see (6) and (8)] for COT from the measured transmission function at the first channel T_1, surface albedo A_1, and asymmetry parameter g_1, which depends on the effective radius a_{ef} (3). Taking into account that COT is generally spectrally neutral over the spectral range of interest, we may replace τ_2 in (5) with (8) to derive the transcendental equation $T_2 - f(a_{\mathrm{ef}}) = 0$, where $f(a_{\mathrm{ef}})$ is the right-hand side of (5). Instead of spectrally neutral transmittance, we assume that $\tau_2 = B\tau_1$, where $B = s(\lambda_2)/s(\lambda_1)$ [see (3)], and apply Brent's method [1] for determining the root (a_{ef}) of the corresponding transcendental equation. After determining the effective radius, COT is derived from (8), and LWP, proportional to the product of ER and COT, is derived from (3). In addition to the DCM, we have developed the ratio method (RM), where the value of the COT $\tau_2 = B\tau_1$ is substituted not in (4) but into the ratio of transmittance [as determined from (4)] at the wavelength $\lambda_3 = 1634$ nm to that at $\lambda_2 = 1548$ nm. The RM can be used only when multispectral measurements are available.

Retrieval results from this new technique are shown in Fig. 2 for synthetic data derived from exact radiative transfer calculations and under the assumption of an underlying black surface and the gamma PSD given previously. Analysis of these results shows that the COT can be retrieved accurately using both DCM and RM when COT is larger than 10. The retrievals of the ER with the DCM are less reliable at COTs below approximately 20, an independent confirmation of the study performed in [10]. The use of the RM increases the accuracy of the ER retrieval for COT in the range of 10–20 [see Fig. 2(b)] and leads to results that are similar to those derived from the DCM for the values of COT larger than 20.

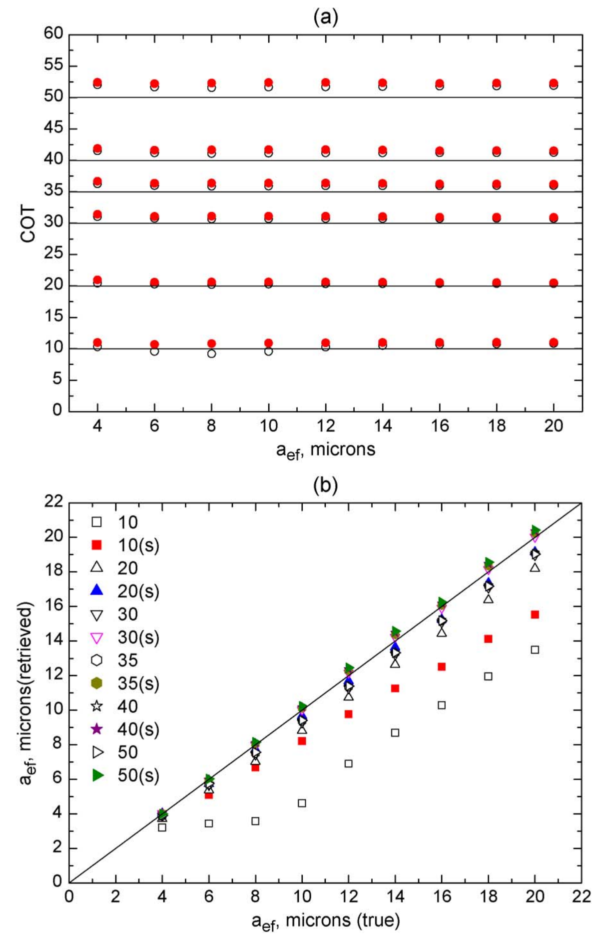

Fig. 2. Errors of synthetic retrievals for (a) COT and (b) ER as functions of the effective radius for COT of 10, 20, 30, 35, 40, and 50. Other parameters are the same as in Fig. 1. Open symbols represent retrievals using the dual-channel inversion algorithm. The filled symbols correspond to the retrievals based on the spectral measurements. In particular, it was assumed that the measurements are performed at three channels (865, 1548, and 1634 nm), and the RM was applied.

We have also applied the DCM to the experimental data of [11], a study comparing surface, satellite, and airborne cloud observations. The data were collected in support of the research at the Nexus of Air Quality and Climate Change Campaign which was aimed at studying the interactions between air quality and climate. It was conducted in May and June 2010 and involved three aircraft, one ship, and several ground sites. The data relevant to this work were from the Solar Spectral Flux Radiometer (SSFR) [13] which was deployed on the R/V Atlantis, a ship operated by the Woods Hole Oceanographic Institute. Part of the study in [11] focused on one particular cloudy day, May 16, 2010, which featured coordinated observations from the Atlantis and the NOAA WP-3D. The DCM algorithm was applied to 1 h of these data that were chosen for the overcast

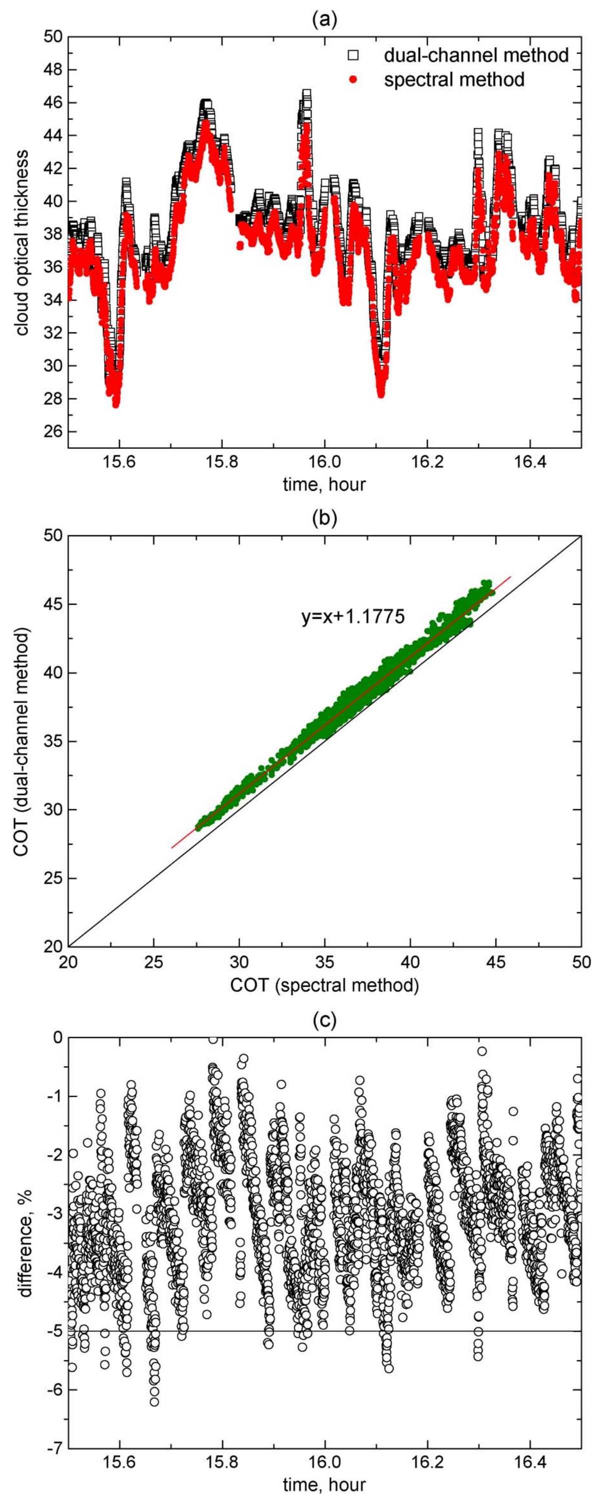

Fig. 3. (a) Values of COT as retrieved from the experimental data presented in [11] using the spectral method and from the DCM using the exponential approximation. (b) Correlation between retrievals. (c) Difference between retrievals.

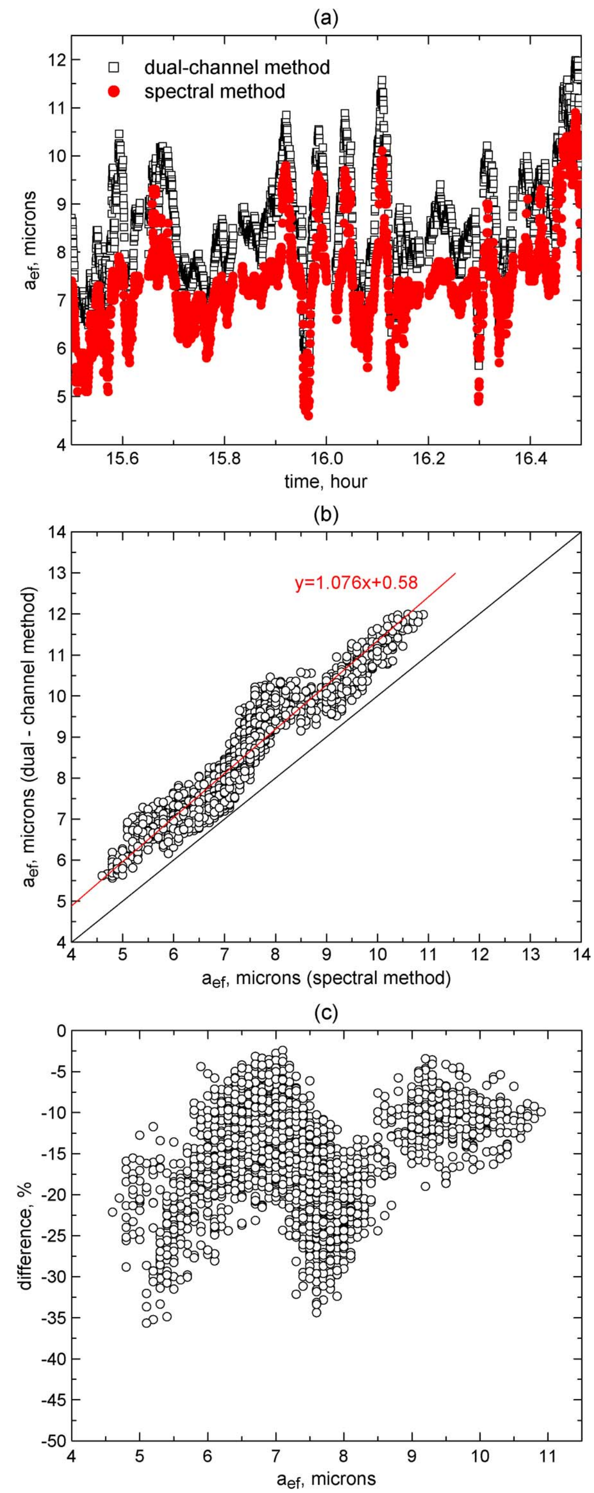

Fig. 4. (a) Values of COT as retrieved from the experimental data presented in [11] using the spectral method and from the DCM using the exponential approximation. (b) Correlation between retrievals. (c) Difference between retrievals as function of the effective radius.

conditions and the relative thickness of the observed clouds. The data were taken over the Pacific Ocean off the coast of Los Angeles between 15.5 and 16.5 UTC.

The DCM results are shown in Figs. 3 and 4, along with those derived using the spectral method of [10]. It is evident that these independent retrieval methods produce similar results for the COT. The average COT values derived from the DCM and from the spectral method were 38.3 and 37.1, respectively. The retrievals from the two methods are in close agreement, differing by only 3%, which may be explained by different assumptions on the PSD, surface reflectance, and atmospheric state in the two retrieval procedures. The differences in the retrieved effective radii using the spectral method and the DCM are larger, 16% on average, and do not exceed 40%

for any case (see Fig. 4). This is an acceptable difference, especially considering that there are differences in the assumed atmospheric states used in the two retrievals and it is within the uncertainty of the measurements. The average effective radius retrieved using DCM is 8.5 μm and that derived using spectral method is 7.4 μm for the whole data set presented in this paper. Also, note that, for the retrievals based on the spectral method, transmittances at 551, 1536, and 1634 nm were used, different from those used in the DCM (865 and 1548 nm). This may also contribute to the differences in the retrievals, along with vertical inhomogeneities that are likely present within the cloud layers [11].

IV. Conclusion

We have introduced a simple and robust methodology to retrieve the COT and cloud effective radius using the measurements of transmitted diffuse solar radiation. The method can be applied to the values of COTs larger than approximately 10. The clouds with smaller optical thickness are often horizontally inhomogeneous, which will lead to a bias in the retrievals, and the requisite information content for separating the effects from cloud particle size from those due to COT is less than that from thicker clouds. In general, the accuracy of COT retrievals is more accurate than retrievals of the effective radius. The clouds during the experiment were vertically inhomogeneous, so the derived ER may be interpreted to be derived from a specific level in the cloud. This level depends on the channels used in the retrievals due to the dependence of the corresponding weighting functions with wavelength. The technique was applied to water clouds. The application of the method to the ice cloud cases is similarly straightforward.

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